

REMARKS

Claims 10-28 are pending in this application. By this Preliminary Amendment, Applicants AMEND the specification and the abstract of the disclosure, CANCEL claims 1-9 and ADD new claims 10-28.

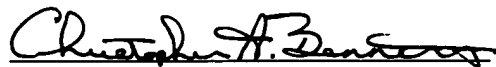
Applicants have attached hereto a Substitute Specification in order to make corrections of minor informalities contained in the originally filed specification. Applicants' undersigned representative hereby declares and states that the Substitute Specification filed concurrently herewith does not add any new matter whatsoever to the above-identified patent application. Accordingly, entry and consideration of the Substitute Specification are respectfully requested.

The changes to the specification have been made to correct minor informalities to facilitate examination of the present application.

Applicants respectfully submit that this application is in condition for allowance. Favorable consideration and prompt allowance are respectfully solicited.

Respectfully submitted,

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DESCRIPTION

Attorney Docket No. 36856.1310

SEMICONDUCTOR DEVICE AND METHOD FOR MANUFACTURING

5 SEMICONDUCTOR DEVICE

TECHNICAL BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a semiconductor device
10 and a method for manufacturing the semiconductor device. In
particular, the present invention relates to a semiconductor
device in which zinc oxide is used as a semiconductor
material and to a method for manufacturing the semiconductor
device.

15

~~Background~~ 2. Description of the Related Art

Zinc oxide (ZnO) is one type of II-VI compound
semiconductors. The band gap energy of ZnO can be changed
by making ZnO into a mixed crystal with MgO, CdO, or ~~the~~
20 ~~like~~ other suitable materials, and ZnO can have a multilayer
structure of quantum well and ~~the like~~ other suitable
structures. Furthermore, since the bond energy of an
exciton is very large, ~~an application to ZnO is suitable for~~
use in light-emitting devices is expected. Since ZnO is
25 transparent in the visible range, ~~an application to ZnO is~~

also suitable for use in transparent thin film transistors
for driving liquid crystal displays ~~is expected~~.

Meanwhile, ZnO has a wurtzite structure (hexagonal
system). As shown in Fig. 9, ZnO has no center of symmetry
5 in the c axis direction (vertical direction) and has
polarity based on a molecular structure.

That is, ZnO has zinc-polarity (+c polarity) in which
three bonds bonding to a Zn atom 51 point downward and three
bonds bonding to an oxygen atom 52 point upward, as shown in
10 Fig. 9(a), and oxygen-polarity (-c polarity) in which three
bonds bonding to a Zn atom 51 point upward and three bonds
bonding to an oxygen atom 52 point downward, as shown in Fig.
9(b).

Here, the above-described polarity refers to an
15 orientation of the above-described bond and does not refer
to an element terminating the surface.

It has been ~~already~~ reported that a ZnO thin film
having the oxygen-polarity was previously ~~able to be~~ formed
by a PMBE (plasma-assisted molecular-beam epitaxy) method on
20 a sapphire substrate (APPLIED PHYSICS LETTERS, Vol. 80, No.
8, pp. 1358-1360 (2002); hereafter referred to as "first
known technology").

It has been reported that a film of GaN having Ga-
polarity was formed on a sapphire substrate and, by
25 controlling the film formation conditions, a ZnO thin film

having the zinc-polarity or the oxygen-polarity was ~~able to be~~ formed on the above-described GaN (APPLIED PHYSICS LETTERS, Vol. 77, No. 22, pp. 3571-3573 (2000); hereafter referred to as "second known technology").

5 In addition, ~~a~~ another technology has been ~~already~~ reported, in which the polarity of a piezoelectric film of ZnO ~~or the like~~ formed on a substrate was able to be specified (Japanese Unexamined Patent Application Publication No. 2001-144328; hereafter referred to as "third
10 known technology"), as another known technology.

 In the above-described third known technology, a piezoelectric film (ZnO film) having a + surface (zinc-polarity) or a - surface (oxygen-polarity) can be formed in accordance with the type of substrate, and the polarity of
15 the piezoelectric film of ZnO ~~or the like~~ formed on a substrate is controlled by changing the film formation conditions, e.g., a heating temperature of the substrate.

 With respect to the above-described first known technology, ~~although~~ it has been ~~ascertained~~ determined by
20 Coaxial Impact Collision Ion Scattering Spectroscopy (CAICISS) that the ZnO thin film formed on the sapphire substrate has ~~the~~ oxygen-polarity. However, substantially hexagonal crystal grains remain in such a ZnO film, the surface shape becomes uneven and, thereby, ~~no ZnO thin film~~
25 ~~having the~~ desired surface smoothness ~~can be attained.~~

~~That is, since the surface shape of the ZnO thin film~~
cannot be obtained.

That is, since the ZnO thin film formed by the first
known technology has poor surface smoothness, ~~in the case~~
5 where a semiconductor device is formed ~~by the use of~~ using
the ZnO thin film, a current passes through grain boundaries,
and ~~the a~~ a concentration of electric field occurs on convex
portions of crystal grains. Consequently, the operation of
the device may become unstable, or the device may be
10 ~~destructed~~ destroyed.

According to the second known technology, the polarity
of the ZnO thin film can be controlled by changing the film
formation conditions. In this manner, the ZnO thin film
having the zinc-polarity or the oxygen-polarity can be
15 formed on GaN. However, the substrate temperature
~~riser~~ increases during the film formation of ZnO on GaN and,
thereby, Ga, which is an element ~~constituting of~~ constituting GaN, may
diffuse into the ZnO thin film.

Since Ga ~~performs a function~~ functions as a donor to ZnO,
20 if Ga diffuses into the ZnO thin film, the resistance of ZnO
is reduced.

Furthermore, it is difficult to control the above-
described diffusion and, therefore, variations may
~~result~~ occur in the device characteristics of the
25 semiconductor device.

In the above-described second known technology, since there is lattice mismatch between GaN and ZnO, lattice defects are introduced to mitigate the lattice mismatch. As a result, the crystallinity of the ZnO thin film is
5 deteriorated and, thereby, deterioration of the electric characteristics ~~results in~~occurs.

The above-described third known technology discloses the formation of the piezoelectric thin film having the zinc-polarity or the oxygen-polarity. However, there is no
10 disclosure with respect to the influence exerted by the polarity on the surface shape and the electric characteristics of the thin film. Furthermore, since the material for the substrate is different from the material for the piezoelectric film, deterioration of the
15 crystallinity may ~~result from~~occur due to the lattice mismatch as in the second known technology, and there is a problem in that highly reliable, ~~desired~~desirable, and excellent electric characteristics cannot be
~~attained~~obtained.

20 ~~The~~ _

SUMMARY OF THE INVENTION

To overcome the problems described above, preferred
embodiments of the present invention has been made in
consideration of the above-described circumstances.
25 ~~Accordingly, it is an object of the present invention to~~

provide a semiconductor device, which is provided with a ZnO thin film having excellent surface smoothness and which has excellent crystallinity and excellent electric characteristics, and a method for manufacturing the semiconductor device.

~~Disclosure of Invention~~

—The inventors of the present invention conducted intensive research in order to ~~attain~~obtain a ZnO thin film having excellent surface smoothness. As a result, it was ~~found out~~discovered that a semiconductor device having excellent surface smoothness and crystallinity and excellent electric characteristics ~~was able to be attained~~could be obtained by forming a ZnO thin film on a zinc-polar surface of a single crystal substrate, ~~primarily containing~~including zinc oxide.

~~The present invention was made based on the above-described founding.~~—A semiconductor device according to a preferred embodiment of the present invention is characterized in that includes a single crystal substrate primarily ~~containing~~including zinc oxide which has a zinc-polar surface and an oxygen-polar surface and at least one layer of thin film primarily ~~containing~~including zinc oxide is disposed on the above-described zinc polar surface. In this manner, ~~the~~a thin film having excellent surface

smoothness and crystallinity ~~can be formed~~ is produced.

The inventors of the present invention examined the polarity of the above-described thin film, and it was ~~made clear~~ confirmed that the thin film had zinc-polarity.

5 Therefore, the semiconductor device according to a preferred embodiment of the present invention is ~~characterized in that~~ includes the above-described thin film ~~has having~~ the zinc-polarity. That is, ~~it is clear that a~~ ZnO-based thin film formed on a zinc-polar surface of a ZnO
10 substrate has the zinc-polarity.

~~The~~ In the semiconductor device according to preferred embodiments of the present invention ~~is characterized in that,~~ the above-described thin film is composed of a multilayer film, and the multilayer film ~~constituted~~ defines a
15 light-emitting layer or a switching portion.

Specifically, the above-described thin film is composed of the multilayer film, the multilayer film ~~constitutes~~ defines the light-emitting layer and, therefore, the light-emitting layer has excellent surface smoothness
20 and crystallinity. Consequently, a light-emitting device, e.g., LED and LD, having excellent electric characteristics ~~can be attained~~ is obtained.

Alternatively, the above-described thin film is composed of the multilayer film, the multilayer film
25 ~~constitutes~~ defines the switching portion and, therefore,

even when light is applied to an active layer, ~~change~~changes
in the electrical conductivity ~~can be suppressed~~are
minimized. Consequently, semiconductor devices, e.g., TFT,
capable of preventing deterioration of the characteristics
5 of the switching element ~~can be~~are readily ~~attained~~obtained.

Since the above-described semiconductor device is
provided with a ZnO-based multilayer film having excellent
surface smoothness and crystallinity, semiconductor devices,
e.g., light-emitting elements and thin film transistors,
10 having excellent electric characteristics ~~can be~~are readily
~~attained~~obtained.

A method for manufacturing a semiconductor device
according to preferred embodiments of the present invention
~~is characterized by including~~ includes the steps of
15 determining whether a surface of a single crystal substrate
primarily ~~containing~~including zinc oxide is a zinc-polar
surface or ~~a~~ an oxygen-polar surface, and forming at least
one layer of thin film primarily ~~containing~~including zinc
oxide on the above-described zinc-polar surface.
20 ~~Furthermore, the method is characterized in that the above-~~
~~described thin film has the zinc polarity.~~

According to the above-described manufacturing method,
a desired ZnO-based thin film ~~can be~~ is readily and reliably
formed on the zinc-polar surface of the zinc oxide substrate.

25 That is, after determining whether the surface of the

ZnO substrate is a zinc-polar surface or a ~~an~~ oxygen-polar surface, at least one layer of thin film primarily ~~containing~~ including ZnO is formed on the above-described zinc-polar surface. Since the above-described ZnO thin film
5 has ~~the~~ zinc-polarity, the ZnO-based thin film ~~can be~~ is readily formed on the zinc-polar surface.

The semiconductor device according to preferred
embodiments of the present invention is ~~characterized in~~
~~that~~ preferably formed using a sputtering apparatus provided
10 with a plasma generation chamber and a film formation
~~chamber is disposed and a.~~ A sputtering treatment is
~~performed by the use of~~ using the sputtering apparatus so as
to form the above-described thin film.

According to the above-described manufacturing method,
15 since the film is formed by the sputtering treatment, a
semiconductor device having desired electric characteristics
~~can be attained~~ is obtained inexpensively. Furthermore,
since the plasma generation chamber and the film formation
chamber are separated, plasma damage to the semiconductor
20 device ~~can be~~ is minimized.

Preferably, the above-described sputtering treatment is
performed by any method selected from ~~among~~ an electron
cyclotron resonance plasma sputtering method, an inductively
coupled plasma sputtering method, a helicon wave excited
25 plasma sputtering method, an ion beam sputtering method, and

a cluster beam sputtering method. Alternatively, the above-described thin film is performed preferably by any method selected from among a molecular-beam epitaxy method, a metal organic chemical vapor deposition method, a laser molecular-beam epitaxy method, and a laser abrasion method.

~~Brief Description of the Drawings~~

Other features, elements, steps, characteristics and advantages of the present invention will become more apparent from the following detailed description of preferred embodiments with reference to the attached drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic sectional view of an ~~embodiment~~ (a first preferred embodiment) of a semiconductor device according to the present invention.

Fig. 2 is a diagram showing polar characteristics of ZnO.

Fig. 3 is a sectional view schematically showing the surface shape of a ZnO thin film formed on a zinc-polar surface of a ZnO substrate.

Fig. 4 is a diagram showing polar characteristics of a ZnO thin film formed on the zinc-polar surface of the ZnO substrate.

Fig. 5 is a schematic sectional view of a second preferred embodiment of the semiconductor device according to the present invention.

Fig. 6 is a schematic sectional view of a preferred
5 third embodiment of the semiconductor device according to the present invention.

Fig. 7 is a micrograph showing the surface shape of a ZnO thin film formed on a zinc-polar surface of a ZnO substrate.

10 Fig. 8 is a micrograph showing the surface shape of a ZnO thin film formed on an oxygen-polar surface of the ZnO substrate.

Fig. 9 is a diagram showing a crystal structure of ZnO.

15 ~~Best Mode for Carrying Out the Invention~~

~~—~~ THE DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

Preferred embodiments of the present invention will be described below in detail with reference to the drawings.

Fig. 1 is a schematic sectional view of a Light
20 Emitting Diode (hereafter referred to as "LED") as an ~~embodiment~~ ~~(a first preferred embodiment)~~ of a semiconductor device according to the present invention.

In Fig. 1, reference numeral 1 denotes a single crystal substrate primarily ~~containing~~ including electrically
25 conductive ZnO having an n-type conduction form (hereafter

referred to as "ZnO substrate"), and the ZnO substrate 1 has a zinc-polar surface 1a and an oxygen-polar surface 1b.

In the LED, a light-emitting layer 2 is disposed on the zinc-polar surface 1a of the ZnO substrate 1, and a
5 transparent electrode 3 ~~of about 150 nm in film thickness~~
made of Indium Tin Oxide (hereafter referred to as "ITO")
and having a film thickness of about 150 nm is disposed on
the surface of the light-emitting layer 2. Furthermore, a
p-side electrode 4 having a total film thickness of about
10 300 nm is disposed on a substantially central portion of the
surface of the transparent electrode 3, while a Ni film, an
Al film, and a Au film are laminated sequentially in the p-
side electrode 4.

An n-side electrode 5 having a total film thickness of
15 about 300 nm is disposed on the oxygen-polar surface 1b of
the ZnO substrate 1, while a Ti film and a Au film are
laminated sequentially in the n-side electrode 5.

Specifically, the above-described light-emitting layer
2 ~~is composed of~~ includes a multilayer film in which an n-
20 type contact layer 6, an n-type clad layer 7, an active
layer 8, a p-type clad layer 9, and a p-type contact layer
10 are laminated sequentially. That is, the active layer 8
is ~~held~~ disposed between the n-type clad layer 7 and the p-
type clad layer 9, the n-type clad layer 7 is connected to
25 the n-side electrode 5 with the n-type contact layer 6 and

the ZnO substrate 1 therebetween, and the p-type clad layer 9 is connected to the transparent electrode 3 with the p-type contact layer 10 therebetween.

The active layer 8 is formed from $\text{Cd}_x\text{Zn}_{1-x}\text{O}$ (where x satisfies $0 \leq x < 1$, and is about 0.1, for example) which is a mixed crystal of CdO and ZnO and which has a film thickness of about 200 nm.

 The active layer 8 emits light by recombination of an electron which is an n-type carrier and a hole which is a p-type carrier, and the wavelength of the emitted light is determined by the band gap energy.

Since carriers must be effectively confined in the active layer 8, the n-type clad layer 7 and the p-type clad layer 9 have ~~the~~ a band gap energy larger than that is greater than that of the above-described active layer 8, and are composed of $\text{Mg}_y\text{Zn}_{1-y}\text{O}$ (where y satisfies $0 \leq y < 1$, and is about 0.2, for example) which is a mixed crystal of MgO and ZnO. The n-type clad layer 7 ~~is formed to have the~~ has a film thickness of about 2,000 nm, and the p-type clad layer 9 ~~is formed to have the~~ has a film thickness of about 600 nm.

Both the n-type contact layer 6 and the p-type contact layer 10 are formed from ZnO and have a film thickness of about 200 nm ~~in film thickness~~.

A method for manufacturing the above-described LED will be described below.

Initially, a ZnO single crystal is prepared by a SCVT (Seeded Chemical Vapor Transport) method or ~~the like other~~ suitable method. A surface perpendicular to the c axis direction of the crystal axis is cut from the ZnO single crystal and is subjected to mirror polishing, ~~sesuch~~ such that a ZnO substrate is prepared and the polarity thereof is checked.

Examples of known methods for determining the polarity of a compound semiconductor, e.g., ZnO, having a piezoelectric property include a Coaxial Impact Collision Ion Scattering Spectroscopy (CAICISS) method (APPLIED PHYSICS LETTERS, Vol. 72, (1998+), p. 824), a Convergent Beam Electron Diffraction (CBED) method (APPLIED PHYSICS LETTERS, Vol. 69, (1996+), p. 337), and a Scanning Nonlinear Dielectric Microscopy (SNDM) method (Sentangijutsu Symposium, "Atsuden-zairyo to Danseiha Device," (High Technology Symposium, "Piezoelectric Material and Elastic Wave Device"), (February, 2000) pp. 23-30). In the present preferred embodiment, the polarity of the ZnO substrate is checked by the SNDM (Scanning Nonlinear Dielectric Microscopy) method.

That is, in the SNDM, when a potential is applied while a ~~probe is made to scan~~ probe scans the ZnO substrate 1, an intensity signal incorporating the polarity of the ZnO substrate 1 is detected.

On the other hand, when the applied potential is "0",

since the potential is not applied, no intensity signal incorporating the polarity is detected.

In the SNDM method, when a potential is applied to the ZnO substrate 1, the intensity signal is displaced to the + side or the - side as compared with ~~that in the case where~~ to when the applied potential is "0".

Therefore, in the SNDM method, the intensity at an applied potential of "0" is taken as the reference signal, and the intensity signal when a potential is applied while ~~the prove is made to scan~~ probe scans the ZnO substrate 1 is taken as the polarity signal. Then, the polarity of the ZnO substrate ~~can be~~ is determined based on the displacement of the polarity signal toward the + side or the - side relative to the reference signal.

In the present preferred embodiment, the displacement of the polarity signal toward the - side relative to the reference signal indicates the + polarity (zinc-polarity), and the displacement of the polarity signal toward the + side relative to the reference signal indicates the - polarity (oxygen-polarity) based on the configuration of the SNDM.

Figs. 2(a) and 2(b) are diagrams showing the polar characteristics of the ZnO substrate 1. The horizontal axis indicates the scanning length (μm), and the vertical axis indicates the intensity (a.u. + indicates arbitrary unit).

In Figs. 2(a) and 2(b), the direction indicated by ~~an~~ the arrow X represents the polarity signal of the ZnO substrate 1, and the direction indicated by ~~an~~ the arrow X' represents the reference signal when no potential is applied.

5 Therefore, ~~it can be determined that~~ when the polarity signal is displaced toward the - side relative to the reference signal as shown in Fig. 2(a), the polar surface of the ZnO substrate 1 is a zinc-polar surface, and when the polarity signal is displaced toward the + side relative to
10 the reference signal as shown in Fig. 2(b), the polar surface of the ZnO substrate 1 is an oxygen-polar surface.

After the polarity of the ZnO substrate 1 is determined as described above, a ZnO thin film is laminated on the zinc-polar surface 1a of the ZnO substrate 1 by ~~the use of~~
15 an Electron Cyclotron Resonance (hereafter referred to as "ECR") sputtering apparatus.

That is, the ECR sputtering apparatus ~~separated~~ into having a plasma generation chamber and a separate film formation chamber is ~~prepared~~ provided, the ZnO substrate 1
20 is ~~set~~ disposed at a predetermined position in the film formation chamber with the zinc-polar surface 1a facing up, and the ZnO substrate 1 is heated to a temperature of about 300°C to about 800°C.

Subsequently, a reactive gas, e.g., oxygen, and a
25 plasma generation gas, e.g., argon, are supplied to the

plasma generation chamber, and a microwave is discharged at a frequency (e.g., about 2.45 GHz) at which resonance occurs in the cyclotron, ~~so~~such that plasma is generated in the plasma generation chamber.

5 Thereafter, a high-frequency power (for example, about 150 W) is applied to a sputtering target, and a sputtering target substance (ZnO) is sputtered ~~by using~~ the ~~use of~~ plasma generated in the plasma generation chamber, ~~so~~such that the n-type contact layer 6 made of ZnO is formed on the
10 surface of the ZnO substrate 1 by reactive sputtering.

Next, the reactive sputtering is performed ~~by the use of~~fusing a target produced by sintering MgO and ZnO at a desired mixing ratio, ~~so~~such that the n-type clad layer 7 made of $Mg_yZn_{1-y}O$ (where $0 \leq y < 1$) is formed.

15 Likewise, the reactive sputtering is performed, and the active layer 8 made of $Cd_xZn_{1-x}O$ (where $0 \leq x < 1$), the p-type clad layer 9 made of $Mg_yZn_{1-y}O$ (where $0 \leq y < 1$), and the p-type contact layer 10 made of ZnO are formed sequentially.

The film thickness of each thin film is set at a
20 desired film thickness by controlling the reaction time.

The Ti film and the Au film are formed sequentially on the surface of the oxygen-polar surface 1b of the ZnO substrate 1 so as to form the n-side electrode 5 by an evaporation method, the ITO film is formed on the surface of
25 the p-type contact layer 10 by the evaporation method so as

to form the transparent electrode 3 and, thereafter, Ni, Al, and Au are laminated sequentially so as to form the p-side electrode 4.

As described above, in the first preferred embodiment,
5 the light-emitting layer 2 composed of a ZnO-based multilayer film is formed on the zinc-polar surface 1a of the ZnO substrate 1 and, thereby, ZnO-based thin films having excellent surface smoothness are laminated sequentially. As a result, the surface of the n-type clad
10 layer 7 becomes a thin film including a smooth terrace 11 and a linear step 12, as shown in Fig. 3 (magnified diagram of a portion A shown in Fig. 1), and having excellent surface smoothness. Therefore, any crystal grain and any uneven portion ~~do not remain on~~ are eliminated from the
15 surface, and the ZnO thin film having excellent surface smoothness ~~can be attained~~ is obtained.

The thin film having excellent surface smoothness, as shown in Fig. 3, can be ~~attained~~ obtained with respect to not only the n-type clad layer 7, but also the n-type contact
20 layer 6, the active layer 8, the p-type clad layer 9, and the p-type contact layer 10 in a similar manner.

Since the above-described ZnO-based thin films have excellent surface smoothness as described above, no current passes through grain boundaries, ~~nor occur~~ and a
25 concentration of electric field on the surface of the ZnO

film does not occur. Consequently, no scattering occurs during movement of electrons, and an LED having high mobility of electron, excellent crystallinity, and excellent electric characteristics ~~can be attained~~ is obtained.

5 In the above-described first preferred embodiment, since the ECR sputtering apparatus is used and the ZnO-based thin films are formed by the sputtering treatment, no expensive apparatus is required to be ~~disposed~~ separately provided, ~~and~~ and thus, the thin film formation ~~can be~~ is performed inexpensively.

10 Furthermore, since the plasma generation chamber and the film formation chamber are separated, plasma damage to the ZnO thin film ~~can be~~ is minimized, and a thin film having good quality ~~can be attained~~ is obtained.

15 In the present preferred embodiment, the polarity of the ZnO thin film formed on the surface of the ZnO substrate 1 was further examined by the use of the SNDM.

20 That is, the sensitivity of the SNDM in the depth direction is determined based on the ~~probe~~ probe end radius of the ~~probe~~ probe and the dielectric constant of the sample, ZnO. In the case of ZnO, the detectable range in the depth direction is substantially equal to the ~~probe~~ probe end radius of the ~~probe~~ probe. Therefore, by making the above-described ~~probe~~ probe end radius smaller than the film

25 thickness, the polarity of the ZnO thin film can be

determined regardless of the polarity of the ZnO substrate 1
~~serving as~~ which defines the base.

Fig. 4 is a diagram showing the polar characteristics
of the ZnO thin film. As in Figs. 2(a) and 2(b), the
5 horizontal axis indicates the scanning length (μm), the
vertical axis indicates the intensity (a.u.), the direction
indicated by an arrow X represents the polarity signal of
the ZnO substrate 1, and the direction indicated by an arrow
X' represents the reference signal when no potential is
10 applied.

As ~~is clear from~~ shown in Fig. 4, since the polarity
signal is displaced toward the - side relative to the
reference signal, the ZnO thin film has the zinc-polarity.
That is, the ZnO-based thin film formed on the zinc-polar
15 surface of the ZnO substrate 1 has the zinc-polarity.

In the present preferred embodiment, a double
heterostructure is used for the light-emitting layer 2, in
which the active layer 8 is ~~held~~ disposed between the p-type
clad layer 9 and the n-type clad layer 7. However, a pn
20 junction structure, an MIS (Metal-Insulating layer-
Semiconductor layer) structure, or a single heterostructure
may be used.

Fig. 5 is a schematic sectional view of a Laser Diode
(hereafter referred to as "LD") as a second preferred
25 embodiment of the semiconductor device according to the

present invention.

In the LD, a light-emitting layer 14 is disposed on a zinc-polar surface 13a of a ZnO substrate 13 having electrical conductivity, and a p-side electrode 15 having a total film thickness of about 300 nm is disposed on the surface of the light-emitting layer 14, while a Ni film, an Al film, and a Au film are laminated sequentially in the p-side electrode 15.

An n-side electrode 16 having a total film thickness of about 300 nm is disposed on an oxygen-polar surface 13b of the ZnO substrate 13, while a Ti film and a Au film are laminated sequentially in the n-side electrode 16.

Specifically, the above-described light-emitting layer 14 is composed of a multilayer film in which an n-type contact layer 17, an n-type clad layer 18, an n-type light guide layer 19, an active layer 20, a p-type light guide layer 21, a p-type clad layer 22, a current limiting layer 23, and a p-type contact layer 24 are ~~laminated~~ sequentially laminated.

That is, the active layer 20 is ~~held~~disposed between the n-type clad layer 18 and the p-type clad layer 22 with the n-type guide layer 19 and the p-type guide layer 21 therebetween, respectively.

The n-type clad layer 18 is connected to the n-side electrode 16 with the n-type contact layer 17 and the ZnO

substrate 13 therebetween, and the p-type clad layer 22 is connected to the p-side electrode 15 with the current limiting layer 23 and the p-type contact layer 24 therebetween.

5 Specifically, the active layer 20 has a multi-quantum well structure in which 2 to 5 layers of a barrier layer composed of $\text{Mg}_y\text{Zn}_{1-y}\text{O}$ (where y satisfies $0 \leq y < 1$, and is about 0.1, for example) and a well layer composed of $\text{Cd}_x\text{Zn}_{1-x}\text{O}$ (where x satisfies $0 \leq x < 1$, and is about 0.1, for
10 example), each having a thickness of about 3 nm, are alternately laminated.

 When the refractive index of the active layer 20 is ~~larger~~greater than those of the n-type clad layer 18 and the p-type clad layer 22, the light ~~can be~~is confined in the
15 active layer 20. However, when the light ~~cannot be~~is not adequately confined since the active layer 20 is a thin film, the leakage of the light from the active layer 20 must be prevented. Consequently, the n-type light guide layer 19 having a refractive index between those of the n-type clad
20 layer 18 and the active layer 20 is interposed between the active layer 20 and the clad layer 18, and the p-type light guide layer 21 having a refractive index between those of the p-type clad layer 22 and the active layer 20 is interposed between the active layer 20 and the clad layer 22
25 to ~~constitute a part~~ define a portion of an optical

waveguide.

The n-type contact layer 17 having a film thickness of
about 1,500 nm ~~in film thickness and~~ made of ZnO is disposed
on the zinc-polar surface 13a of the ZnO substrate 13. The
5 n-type clad layer 18 having a film thickness of about 2,000
nm ~~in film thickness and~~ made of $Mg_yZn_{1-y}O$ (where y satisfies
 $0 \leq y < 1$, and is about 0.2, for example) is disposed on the
surface of the n-type contact layer 17. Furthermore, the n-
type light guide layer 19 having a film thickness of about
10 40 nm ~~in film thickness and~~ made of ZnO is disposed on the
surface of the n-type clad layer 18.

The active layer 20 having the above-described multi-
well type structure is laminated on the surface of the n-
type light guide layer 19. The p-type light guide layer 21
15 having a film thickness of about 40 nm ~~in film thickness and~~
made of $Mg_yZn_{1-y}O$ (where y satisfies $0 \leq y < 1$, and ~~is~~ is about
0.2, for example) is disposed on the surface of the active
layer 20. Furthermore, the p-type clad layer 22 having a
film thickness of about 2,000 nm ~~in film thickness and~~ made
20 of $Mg_yZn_{1-y}O$ (where y satisfies $0 \leq y < 1$, and is about 0.2,
for example) is disposed on the surface of the p-type light
guide layer 21.

In addition, in order to pass a current only through an
oscillation region ~~alone~~, the current limiting layer 23
25 ~~of~~ having a film thickness of about 400 nm ~~in film thickness~~

and made of $\text{Mg}_y\text{Zn}_{1-y}\text{O}$ (where y satisfies $0 \leq y < 1$, and is about 0.2, for example) is disposed on the surface of the p-type clad layer 22 ~~while being in~~ and has a predetermined shape having a groove portion 23a. The p-type contact layer 5 24 is disposed on the surface of the p-type clad layer 22 so as to have a cross section in the shape of a letter T while covering the current limiting layer 23.

The above-described LD is also produced by a method and procedure substantially similar to that in the first 10 preferred embodiment of the present invention.

That is, initially, a ZnO single crystal is prepared by the SCVT method or ~~the like~~ other suitable method. A surface perpendicular to the c axis direction of the crystal axis is cut from the ZnO single crystal and is subjected to 15 mirror polishing, ~~so~~ such that a ZnO substrate is prepared and the polarity thereof is checked by the SNDM.

Thereafter, as in the ~~first~~ first preferred embodiment, the ECR sputtering apparatus is prepared, the ZnO substrate 13 is ~~set~~ disposed at a predetermined position in a film 20 formation chamber with the zinc-polar surface 13a up, and the ZnO substrate 1 is heated to a temperature of about 300°C to about 800°C .

Subsequently, the reactive gas, e.g., oxygen, and the plasma generation gas, e.g., argon, are supplied to the 25 plasma generation chamber, and a microwave is discharged,

~~so~~such that plasma is generated in the plasma generation chamber. A sputtering target substance (ZnO) is sputtered, and the n-type contact layer 17 made of ZnO is formed on the surface of the ZnO substrate 13 by reactive sputtering.

5 Likewise, the reactive sputtering is performed while the target substance is appropriately changed to a desired substance, and the n-type contact layer 17, the n-type clad layer 18, the n-type light guide layer 19, the active layer 20, the n-type light guide layer 21, the p-type clad layer
10 22, and the current limiting layer 23 are ~~formed~~ sequentially formed.

 After the current limiting layer 23 is formed, the resulting ZnO substrate 13 provided with the films is temporarily taken out of the sputtering apparatus. A
15 photoresist is applied to the surface of the above-described current limiting layer 23, the resist film is patterned by a known photolithographic technology, and an etching treatment is performed with an alkaline solution, e.g., NaOH, ~~so~~such
 that the current limiting layer 23 is formed into a
20 predetermined shape.

 The above-described ZnO substrate 13 is ~~set~~ again disposed at the predetermined position in the ECR sputtering apparatus, and the reactive sputtering is performed, ~~so~~ such
 that the film of p-type contact layer 24 made of ZnO is
25 formed to have a cross section in the shape of a letter T.

Thereafter, as in the first preferred embodiment, the Ti film and the Au film are ~~formed~~ sequentially formed on the surface of the oxygen-polar surface 13b of the ZnO substrate 13 so as to form the n-side electrode 16 by an
5 evaporation method, and Ni, Al, and Au are ~~laminated~~ sequentially laminated on the surface of the p-type contact layer 24 by the evaporation method so as to form the p-side electrode 15.

As described above, in the second preferred embodiment
10 ~~as well~~, the light-emitting layer 14 composed of a ZnO-based multilayer thin film is formed on the zinc-polar surface 13a of the ZnO substrate 13 as in the first preferred embodiment. Therefore, ZnO-based thin films having a smooth terrace and a linear step ~~can be attained~~ are obtained. In this manner,
15 since excellent surface smoothness is ~~exerted~~ provided, no current passes through grain boundaries, ~~nor occur a~~ concentration of electric field on the surface of the ZnO film does not occur. Consequently, no scattering occurs during movement of electrons, the mobility of electron
20 becomes high, and the crystallinity becomes excellent, ~~sesuch~~ that an LD having excellent electric characteristics ~~can be attained~~ is obtained.

In the above-described second preferred embodiment, as in the first preferred embodiment, since the ECR sputtering
25 apparatus is used and the ZnO-based thin films are formed by

the sputtering treatment, no expensive apparatus is required to be ~~disposed separately~~ provided, and the thin film formation ~~can be~~ is performed inexpensively. Furthermore, since the plasma generation chamber and the film formation
5 chamber are separated, plasma damage to the ZnO thin film ~~can be~~ is minimized, and a thin film having good quality ~~can be attained~~ is obtained.

Fig. 6 is a schematic sectional view of a Thin Film Transistor (hereafter referred to as "TFT") as a third
10 preferred embodiment of the semiconductor device according to the present invention. The TFT ~~is composed of~~ preferably includes an insulating ZnO substrate 25, a gate electrode 26 ~~having a film thickness of about 50 nm in film thickness~~ and disposed on a substantially central portion of the ZnO
15 substrate 25, a gate insulating layer 27 ~~having a film thickness of about 200 nm in film thickness and~~ disposed on the ZnO substrate 25 while covering the gate electrode 26, an active layer 28 having a film thickness of about 50 nm in
~~film thickness and~~ disposed on the gate insulating layer 27,
20 a channel protective layer 29 having a film thickness of
~~about 200 nm in film thickness and~~ disposed on a substantially central portion of the active layer 28, and a source electrode 30 and a drain electrode 31 which are disposed so as to cover a part ~~portion~~ of the channel
25 protective layer 29 and which have film thicknesses of about

200 nm.

In the above-described TFT, a switching portion ~~is composed of~~includes constituents other than the ZnO substrate 25, that is, the gate electrode 26, the gate
5 insulating layer 27, the active layer 28, the channel protective layer 29, the source electrode 30, and the drain electrode 31. The switching portion ~~made of them~~defined by these elements is disposed on a zinc-polar surface 25a of the ZnO substrate 25.

10 The gate electrode 26, the source electrode 30, and the drain electrode 31 ~~are made to have low resistance~~resistances since ZnO is doped with Ga, and the gate insulating layer 27 and the channel protective layer 29 ~~are made to have high resistance~~resistances since ZnO is
15 doped with Ni.

The active layer 28 is ~~formed from~~made of a non-doped ZnO thin film. The oxygen concentration in the thin film is adjusted by controlling the oxygen partial pressure during the formation of thin film and, thereby, the active layer 28
20 is formed to have n-type conduction.

The above-described TFT can also be readily produced ~~by the use of~~fusing the ECR sputtering and the photolithographic technology substantially similar to that in the first and ~~the second~~ preferred embodiments of the present invention.

25 That is, the ZnO substrate is prepared and, thereafter,

the polarity is determined. Subsequently, the ECR sputtering apparatus is used, and the reactive sputtering is performed while Ga-doped ZnO is ~~served~~provided as a target substance, ~~sesuch~~ that a ZnO film (ZnO:Ga) is formed on a
5 zinc-polar surface 25a of the ZnO substrate 25.

The resulting ZnO substrate 25 is ~~taken out of~~removed from the ECR sputtering apparatus. A photoresist is applied to the above-described ZnO film, the resist film is patterned by a known photolithographic technology and,
10 thereafter, an etching treatment is performed with an alkaline solution, e.g., NaOH, ~~sesuch~~ that the gate electrode 26 is formed.

The reactive sputtering is performed while Ni-doped ZnO is ~~served~~provided as a target substance, the gate insulating
15 layer 27 is formed on the ZnO substrate 25 so as to cover the gate electrode. Subsequently, the reactive sputtering is performed while non-doped ZnO is ~~served~~provided as a target substance and the oxygen partial pressure is controlled, ~~sesuch~~ that the active layer 28 is formed.

20 Then, the reactive sputtering is performed while Ni-doped ZnO is ~~served~~provided as a target substance, ~~sesuch~~ that a ZnO film (ZnO: Ni film) is formed. A photoresist is applied to the resulting ZnO film as ~~in the~~described above-~~description~~, the
25 resist film is patterned by the photolithographic technology

and, thereafter, the etching treatment is performed with an alkaline solution, e.g., NaOH, ~~so~~such that the channel protective layer 29 is formed.

Subsequently, the reactive sputtering is performed
5 while Ga-doped ZnO is ~~served~~provided as a target substance, a photoresist is applied to the resulting ZnO:Ga film as ~~in~~
~~the-described above-description~~, the resist film is patterned by the photolithographic technology, and
thereafter, the etching treatment is performed with an
10 alkaline solution, e.g., NaOH, ~~so~~such that the source electrode 30 and the drain electrode 31 are formed.

As described above, in the third preferred embodiment, since the TFT is formed from a ZnO-based multilayer film, even when the active layer 28 is exposed to light, a change
15 in the electrical conductivity ~~can be~~is effectively suppressed.

That is, ~~in the case where~~ an active layer is formed from amorphous silicon (a-Si) ~~in a previous manner~~, since a-Si becomes electrically conductive by the application of
20 light, the characteristics of the switching element may be deteriorated. On the other hand, in the third preferred embodiment, since the active layer 28 is formed from a ZnO thin film having a band gap of about 3.3 eV and having transparency to ~~the~~ visible light, even when the light is
25 applied to the active layer 28, a change in the electrical

conductivity ~~can be suppressed~~ is minimized, and deterioration of the characteristics of the switching element ~~can be~~ is prevented.

Furthermore, by integrally forming the TFT as an upper
5 portion of a photoelectric conversion element or the LED shown in the first preferred embodiment, the amount of light incident to the photoelectric conversion element can be increased or the amount of light emitted from the light-emitting layer can be increased and, therefore, the
10 proportion of opening ~~can be~~ is increased.

The present invention is not limited to the above-described preferred embodiments.

In the above-described ~~embodiment~~ preferred embodiments, the ZnO-based thin films are preferably formed by the ECR
15 sputtering method. However, an inductively coupled plasma (ICP) sputtering method, a helicon wave excited plasma (HWP) sputtering method, an ion beam sputtering method, a cluster beam sputtering method, or ~~the like~~ other suitable sputtering method may be used. Alternatively, the ZnO-based thin films
20 may be formed by ~~the use of a~~ molecular-beam epitaxy (MBE) method, a metal organic chemical vapor deposition (MOCVD) method, a laser molecular-beam epitaxy (laser MBE) method, a laser abrasion method, or ~~the like~~ other suitable method other than the sputtering method.

25 Specific examples of the present invention will be

described below.

The inventors of the present invention used the ECR sputtering apparatus, formed a ZnO thin film on a zinc-polar surface of a ZnO substrate, and prepared a test piece for
5 Example. Furthermore, a ZnO thin film was formed on an oxygen-polar surface of a ZnO substrate, and a test piece for Comparative example was prepared.

That is, an ECR sputtering apparatus ~~separated~~
~~into~~having a plasma generation chamber and a separate film
10 formation chamber was ~~prepared~~provided. A ZnO substrate was ~~set~~disposed at a predetermined position in the film formation chamber, and the substrate was heated to a temperature of about 620°C.

Subsequently, each of 20 sccm of argon gas serving as a
15 sputtering gas and 10 sccm of O₂ gas serving as a reaction gas was supplied to the plasma generation chamber, and micro-discharge was performed, ~~so~~such that plasma was generated. A high-frequency electric field of about 150 W was applied to a sputtering target, and a sputtering
20 treatment was performed, ~~so~~such that a ZnO thin film was formed on a zinc-polar surface of a ZnO substrate, another ZnO thin film was formed on an oxygen-polar surface of another ZnO substrate and, thereby, test pieces for the Example and the Comparative example were prepared.

25 The inventors of the present invention observed the

surface shapes of the ZnO thin films with an atomic force microscope.

Fig. 7 shows the ZnO thin film of the Example. Fig. 8 shows the ZnO thin film of the Comparative example, formed
5 on the oxygen-polar surface of the ZnO substrate.

As is clear from this Fig. 8, the ZnO thin film of the Comparative example is in the shape of islands and, therefore, grain boundaries are present.

On the other hand, as shown in Fig. 7, ~~it was~~
10 ~~ascertained from the ZnO thin film of the Example that has a~~
~~thin film having the surface shape including a smooth~~
~~terrace and a substantially linear step was able to be~~
~~attained~~ obtained.

Therefore, it was ~~made clear~~ that the ZnO thin film
15 formed on the zinc-polar surface of the ZnO substrate had significantly ~~excellent~~ improved surface smoothness as
compared ~~with to~~ that of the ZnO thin film formed on the oxygen-polar surface of the ZnO substrate.

The inventors of the present invention calculated the
20 root-mean-square surface roughness RMS of the ZnO thin film, and evaluated the surface roughness.

As a result, the root-mean-square surface roughness RMS of the ZnO thin film of the Comparative example was about
20.4 nm, whereas the root-mean-square surface roughness RMS
25 of the ZnO thin film of the Example was about 1.4 nm.

Consequently, it was ~~made~~ clear that the surface smoothness of the ZnO substrate was significantly improved by forming the ZnO thin film on the zinc-polar surface as compared ~~with~~to that in the case where the ZnO thin film was formed
5 on the oxygen-polar surface.

The inventors of the present invention conducted a hole measurement, and calculated the electron mobility.

When the crystallinity is excellent, the mobility is increased because electrons are not scattered ~~due to~~by crystal defects during movement. However, if crystal
10 defects are present, the mobility is decreased because electrons are scattered ~~due to~~by the crystal defects during movement.

Therefore, the level of crystallinity and the electric
15 characteristics can be evaluated by calculating the electron mobility.

The inventors of the present invention ~~laminated~~ sequentially laminated a Ti film and a Au film on each of the ZnO thin films of the Example and the Comparative
20 example by an evaporation method to form an electrode, and conducted the hole measurement so as to measure the electron mobility.

~~As a result, the~~ The electron mobility was about 2 cm²/V·sec in the Comparative example, whereas the electron
25 mobility was ~~a large~~about 30 cm²/V·sec in the Example.

Consequently, it was ascertained that both the crystallinity and the electric characteristics of the Example were ~~excellent~~ greatly improved as compared with to those of the Comparative example.

5

~~Industrial Applicability~~

As described above, the electronic components according to preferred embodiments of the present invention are preferably used as components for image equipment, and are
10 particularly suitable for use as light-emitting elements of optical pickups used in image equipment.

While the present invention has been described with respect to preferred embodiments, it will be apparent to those skilled in the art that the disclosed invention may be
15 modified in numerous ways and may assume many embodiments other than those specifically set out and described above.
Accordingly, it is intended by the appended claims to cover all modifications of the invention which fall within the true spirit and scope of the invention.